**COMPARING RESTRAINT SYSTEM SENSITIVITY BETWEEN THE THOR AND THE HYBRID III, AND POTENTIAL IMPLICATIONS IN RESTRAINT OPTIMIZATION**

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**ABSTRACT**
Restraint system optimization is affected by the sensitivity of dummies to relative loading between the seatbelt and airbag. Differences in design between the THOR and Hybrid III dummies may affect the mechanisms of interaction with the various restraint system components, and the factors that influence compression measured in the dummy's chest. Previous studies have compared dummy responses in sled tests representing select specific configurations. The goal of this study was to compare the mechanisms of chest compression in the THOR and Hybrid III, and sensitivity to loading by various restraint system components, in full vehicle crash tests.

The NHTSA full-vehicle crash test database was queried to find cases of matched tests with the THOR and the Hybrid III. Four cases of matched tests were found - one with a sub-compact hatchback, one with a compact sedan, one with a mid-sized sedan, and one with a full-sized pickup. All were 56 km/h frontal-impact, rigid barrier tests, with the dummy seated in the driver position. The vehicles were matched based on make, model, model base year, and restraint system characteristics (e.g., observed belt force limit). Shoulder belt forces, chest deflection time histories, and frame-by-frame videos were examined to restraint system interaction and factors influencing compression measured in the chest.

In all four cases the shoulder belt force time histories were similar between the THOR and the Hybrid III. In one case the chest compression in the Hybrid III appeared to be predominantly dependent on force limiting in the shoulder belt, while the THOR exhibited a greater sensitivity to combined loading by the belt and airbag. In two cases the results were mixed, with both the dummies exhibiting some sensitivity to both belt and airbag loading (though the airbag appeared to contribute to a greater degree with the THOR). The nature of chest compression appeared most similar in a case of an apparent digressive force limiter, with both dummies exhibiting a plateau associated with a transition to airbag loading with a drop belt force limit.

These results suggest that the relative sensitivity to belt and airbag loading can vary between the THOR and the Hybrid III, depending on the specific characteristics of the restraint system and vehicle being studied. The THOR is more flexible, tends to experience greater forward excursion into the airbag, rides up higher on the airbag, and is capable of measuring deflection in the upper chest where a majority of the airbag loading occurs in some cases. As a result, in some cases the THOR appears to be more sensitive to loading by the airbag than the Hybrid III. Sensitivity to loading by the various restraint system components will likely affect optimization of the restraint systems, affecting the perceived optimal apportionment of load between the belt and the airbag. These results suggest that the two dummies may lead to different strategies for restraint system optimization in some cases, and that the relation of restraint system interaction between the THOR and Hybrid III may vary in the fleet.

## INTRODUCTION

Restraint design relies on evaluation in full vehicle crash tests with anthropomorphic test devices (ATDs, dummies) serving as surrogates for the vehicle occupants. These crash tests challenge the restraint system to provide a balance between applying sufficient force to halt the motion of the occupant, while applying said restraining force in a manner that minimizes risk of injury from loading by the restraints. The risk of injury is commonly assessed through measurements taken from specific internal sensors of the dummy (e.g., force, acceleration, deformation), compared to injury assessment reference values (IARVs) or injury risk functions.

One of the drivers of restraint system optimization for frontal impacts is chest compression (used to estimate chest injury risk), measured by internal sensors arranged to observe the displacement of the ribcage relative to the spine [1-5]. Dummy chest compression may be affected by factors such as position of the shoulder belt, force limiting in the shoulder belt, forward excursion and forward pitch of the torso, and engagement with the airbag and steering wheel [3,6]. Most formalized vehicle crashworthiness evaluation programs utilize dummy chest compression in their frontal impact safety assessments in some manner [7]. Designing restraint systems to address the performance requirements of those programs requires understanding the factors that contribute to chest compression in the dummy, including the mechanisms of engagement with the restraint system components and how they affect compression measurements in the chest.

The Hybrid III 50$^{th}$ percentile male dummy (H3) is currently the primary dummy for frontal impact, belted driver safety assessment for formalized crashworthiness test programs worldwide [8]. Recent efforts have considered a shift towards evaluation with the THOR dummy [9,10]. There are several differences between the two dummies that may result in differences in the manner in which they engage with restraint systems, potentially affecting the factors that influence chest compression measurement. The THOR has a more flexible spine than the H3 [11], potentially affecting the stiffness of coupling between the upper and lower body. This may affect forward excursion of the torso, and the nature in which restraint of the lower body (e.g., via the lap belt) contributes to restraint of the upper body [12-15]. The THOR chest is also more compliant [16], and less coupled [17] than the H3, resulting in more chest compression for a given amount of concentrated load. The THOR includes a shoulder structure with a clavicle, affecting the manner in which shoulder belt engagement translates into compression of the chest [18,19]. The THOR also includes multi-point compression measurement on the chest (compared to single-point measurement in the H3), potentially affecting the observation of chest compression under various patterns of loading [1,14]. Understanding how the dummies will affect restraint system design requires understanding how their differences will affect interactions with the restraint system components, and the factors that influence chest compression measurement (as well as other injury prediction measures).

THOR and H3 responses have been compared previously in sled testing. For example, Kent et al. [1,3] and Petitjean et al. [4] each compared THOR and H3 responses in frontal impact sled tests with various types of airbag and seatbelt systems (e.g., comparing non-force limiting to force-limiting 3-point belts). Others have compared responses in more simplified sled environments designed specifically for biofidelity evaluation under 3-point belt loading [13]. More recently, Albert et al. [20,21] compared THOR and H3 responses to post mortem human surrogates (PMHS) in sled tests with a modern belt and driver airbag system, and with a simulated representation of a knee airbag. While these types of studies provide valuable information in controlled testing environments, they are limited in that they evaluate a single specific scenario (or a small number of scenarios) from among the wide variety of restraint designs and vehicle interior geometries that are present in the fleet. To understand how the dummies will affect restraint design in real crashworthiness testing, comparison should not be limited to a small number of sled tests, but should include evaluation among vehicles with different restraint and interior designs. This may be accomplished by comparing responses in full-vehicle crash tests utilizing the THOR and H3 dummies.

The goal of this study was to compare restraint interactions and mechanisms of chest compression between the THOR and Hybrid III in matched full vehicle crash tests. This was accomplished through a detailed examination of publicly-available frontal crash tests from the NHTSA Vehicle Test Database. Outcomes of interest included chest compression measured by the dummies, and their relation to engagement by various components of the vehicle's restraint system.

## METHODS

NHTSA's publicly-available crash test database was first queried for full vehicle crash tests that included the THOR 50th percentile male crash test dummy as either the driver or the right front passenger. At the time of the search this returned 122 crash tests with the THOR dummy, 116 of which were oblique moving deformable barrier tests and six of which were NCAP-style rigid full frontal barrier tests. These were then cross-referenced with a search for tests with the Hybrid III 50th percentile male dummy, seeking to match on test condition, seating position (e.g., driver vs. passenger), and vehicle make, model, and model base year. As this required matching based on vehicle information, cases that did not include such information were excluded. This cross-reference returned just five cases of tests with the Hybrid III that potentially matched tests with the THOR dummy, all of which were 56 km/h NCAP-style rigid frontal barrier tests. Data from each of the potential matches were then qualitatively examined to ensure that the vehicle responses (via the vehicle acceleration pulse) and restraint system design (via the upper shoulder belt force time history) were comparable. This resulted in exclusion of one of the potential matches, based on differences in the shoulder belt force limit (and thus potentially differences in restraint design version) between the Hybrid III and THOR tests.

Thus, at the time of the query and evaluation there were four cases of vehicles with matched crash tests with both the Hybrid III and THOR 50th percentile male dummies (publicly available from NHTSA). One was a sub-compact hatchback, one was a compact sedan, one a mid-sized sedan, and one a full-sized pickup (Table 1). Each of these included the THOR and Hybrid III in the driver position.

These tests were each examined to observe and compare the restraint interaction factors that contributed to the chest compression measured in the dummies. This included examining the time history of chest compression compared to shoulder belt force, cross-referenced with the high-speed video to identify the engagement with the restraint components at various time points of interest. The THOR is capable of measuring compression at four locations on the chest (upper right and left, lower right and left), compared to one location for the Hybrid III (mid-sternum). The time history of maximum chest compression measured with the THOR (of the four possible measurement locations) was compared to the mid-sternum compression measured with the Hybrid III. Focus was placed not necessarily on comparing the magnitude of chest compression, but instead on comparing the shape of the time history of chest compression and how it relates to the timing of engagement with the restraint system components. Kinematics of the dummies relative to the restraint system components were compared via examination of the high-speed video to elucidate any differences in restraint engagement and mechanisms of chest compression.

*Table 1.*
*Matrix of matched THOR and Hybrid III tests selected from the NHTSA crash test database*.*

| Make, Model | Type | Model Year | Dummy (driver) | NHTSA Test No. | Real Speed (kph) | Notes |
|---|---|---|---|---|---|---|
| Honda Fit | Subcompact hatchback | 2015 | HIII | 9033 | 56.55 | -- |
| | | 2015 | THOR | 9337 | 56.27 | |
| Mazda 3 | Compact sedan | 2014 | HIII | 8539 | 56.39 | -- |
| | | 2015 | THOR | 9336 | 56.61 | |
| Chevrolet Malibu | Mid-sized sedan | 2015 | THOR | 9332 | 56.63 | Includes Knee Airbag |
| | | 2016 | HIII | 7856 | 56.30 | |
| Ford F-150 | Full-sized pickup | 2015 | HIII | 9097 | 56.40 | -- |
| | | 2015 | THOR | 9335 | 56.15 | |

* All full-width rigid frontal barrier tests. Matched tests checked for common base year.

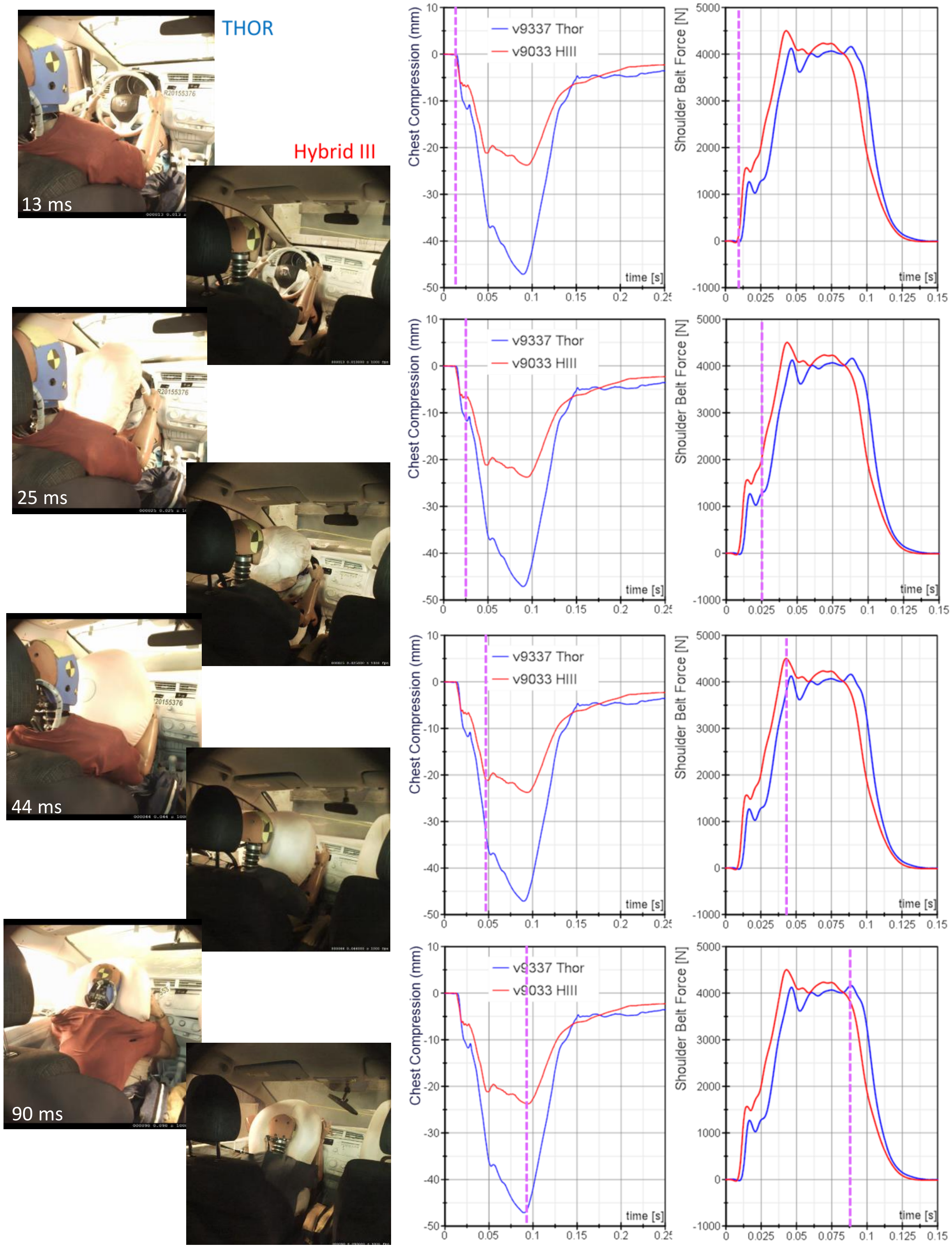

*Figure 1: Video stills, chest compression, and shoulder belt force in the subcompact hatchback comparing the THOR to the Hybrid III. 56 km/h frontal rigid barrier. Chest compression is shown at the peak location for THOR (upper right) and the sternum slider for H3. Pink dashed line - time shown in the video captures.*

**RESULTS**

In all four cases, the peak chest compression in the THOR occurred at the upper right (inboard) measurement location. Figure 1 shows the chest compression and upper shoulder belt force time histories for one pair of matched crash tests (subcompact hatchback), along with high-speed video images at particular timepoints of interest. At approximately 13 ms both dummies begin to move forward and engage the shoulder belt. At 25 ms the airbag has begun to deploy, and force has begun to build in the shoulder belt. At approximately 44 ms the dummies have moved forward enough to begin to engage with the airbag. At this point in time, the belt force has also risen to the point at which the belt force limited begins to yield. As the belt force plateaus the chest compression in the Hybrid III also plateaus, with minimal increase as the dummy moves forward into the airbag. In contrast, the chest compression in the THOR continues to increase as the dummy moves forward into the airbag. In both cases the peak chest compression occurs at the time of peak forward excursion, however the increase in chest compression resulting from forward motion into the airbag was greater with the THOR than the Hybrid III.

Figure 2 shows expanded views of the high speed video images at the approximate time of peak chest compression (90 ms) from the tests discussed above. The approximate locations of peak chest compression measurement are also shown for illustration (upper right for the THOR, compared to the mid-sternum measurement site for the Hybrid III). As can be seen in these images, the THOR appears to ride up higher on the airbag than the Hybrid III (note the location of the top of the top of the head relative to the top edge of the airbag; the location of the shoulders on the airbag; and the angle of the shoulder belt as it leaves the shoulder). This, in combination with the higher measurement location afforded by the upper chest IR-TRACCS, may place the measurement site of peak compression in a position where it can be affected more by engagement with the airbag compared to the Hybrid III.

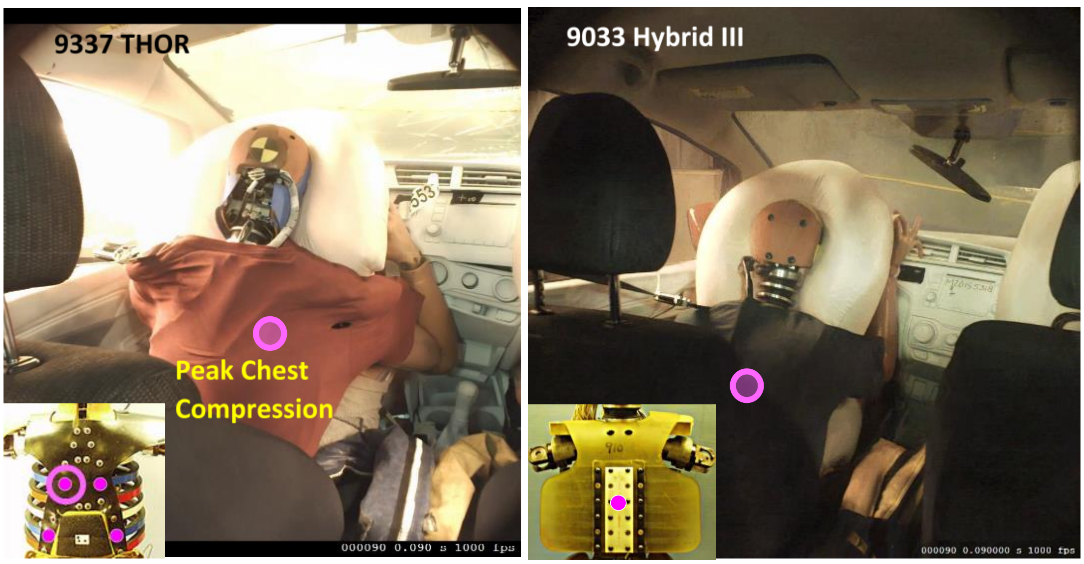


*Figure 2: Screen captures at the time of peak chest compression, illustrating the approximate location of peak chest compression measurement in the THOR, compared to the Hybrid III.*

Figure 3 shows the chest compression and belt force time histories for two of the other pairs of matched tests (the compact sedan and the mid-sized sedan), as well as high speed video stills at the approximate time of peak chest compression measured in the THOR. As with the tests above, the chest compression measured in the THOR continues to rise after the belt force limiter yields, increasing as the dummy moves forward into the airbag. The chest compression in the Hybrid III also continues to increase after the time at which the belt force limiter begins to yield, but plateaus at a time prior to when the peak chest compression was observed with the THOR. Though the video views are not as directly as comparable as with the test above, it appears that the THOR rides up higher on the airbag than the Hybrid III in these tests as well (for example, based on the height of the shoulders relative to the airbag at the time of peak chest compression).

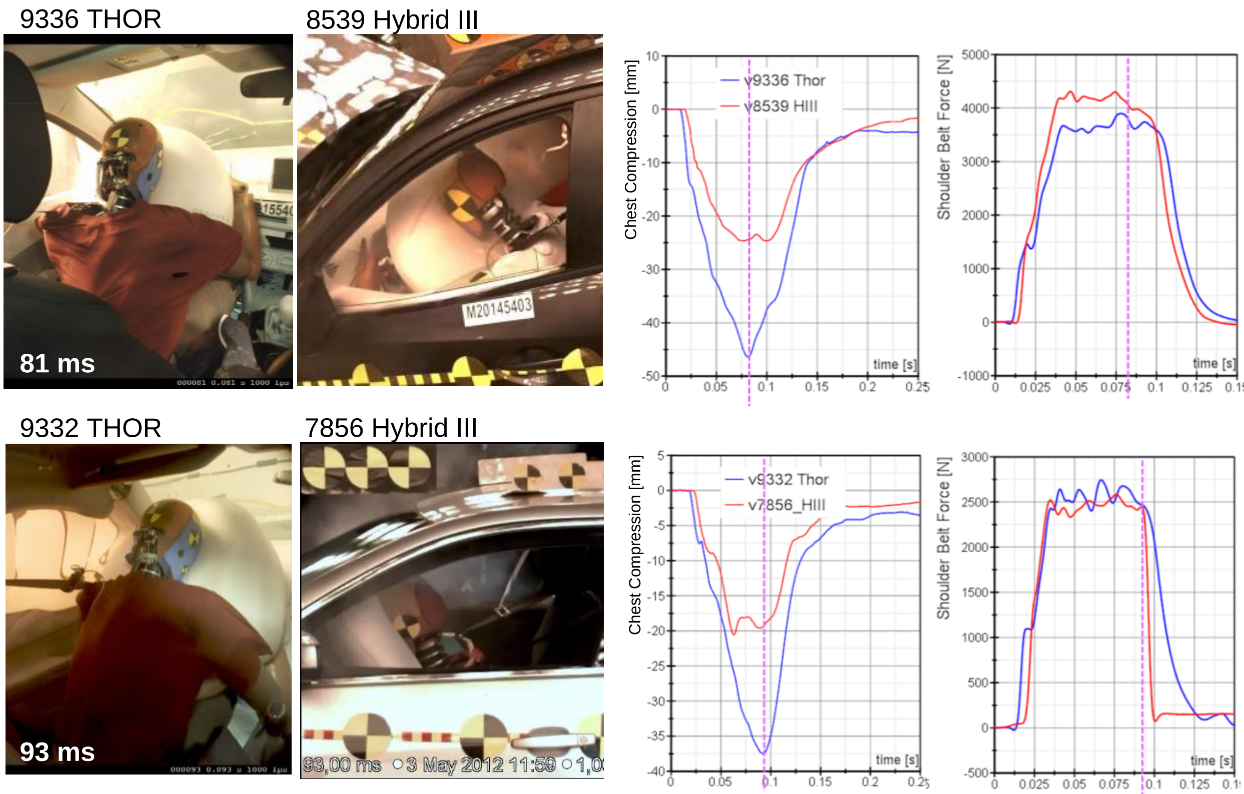


*Figure 3: Chest compression, shoulder belt force, and video stills at the time of peak chest compression in the compact and mid-sized sedans. 56 km/h frontal rigid barrier. Chest compression is shown at the peak location for THOR (upper right) and the sternum slider for H3. Pink dashed line - time shown in the video captures.*

Figure 4 shows the results for the full-sized pickup, with video stills from two timepoints of interest. Unlike the other tests, in this case the THOR chest compression exhibits a plateau similar in nature to that observed with the Hybrid III. This plateauing response occurs in conjunction with a drop in upper shoulder belt force from what appears to be a digressive force limiter. As can be seen from the video stills, the drop in shoulder belt force occurs approximately at the time at which the chest begins to engage with the airbag. There is a brief dip in chest compression in the THOR coinciding with the drop in belt force. This may be attributable to a brief offloading of the chest as the belt force drops, transitioning to increased loading by the airbag as the dummy moves forward. This plateauing behavior is also observed in the Hybrid III.

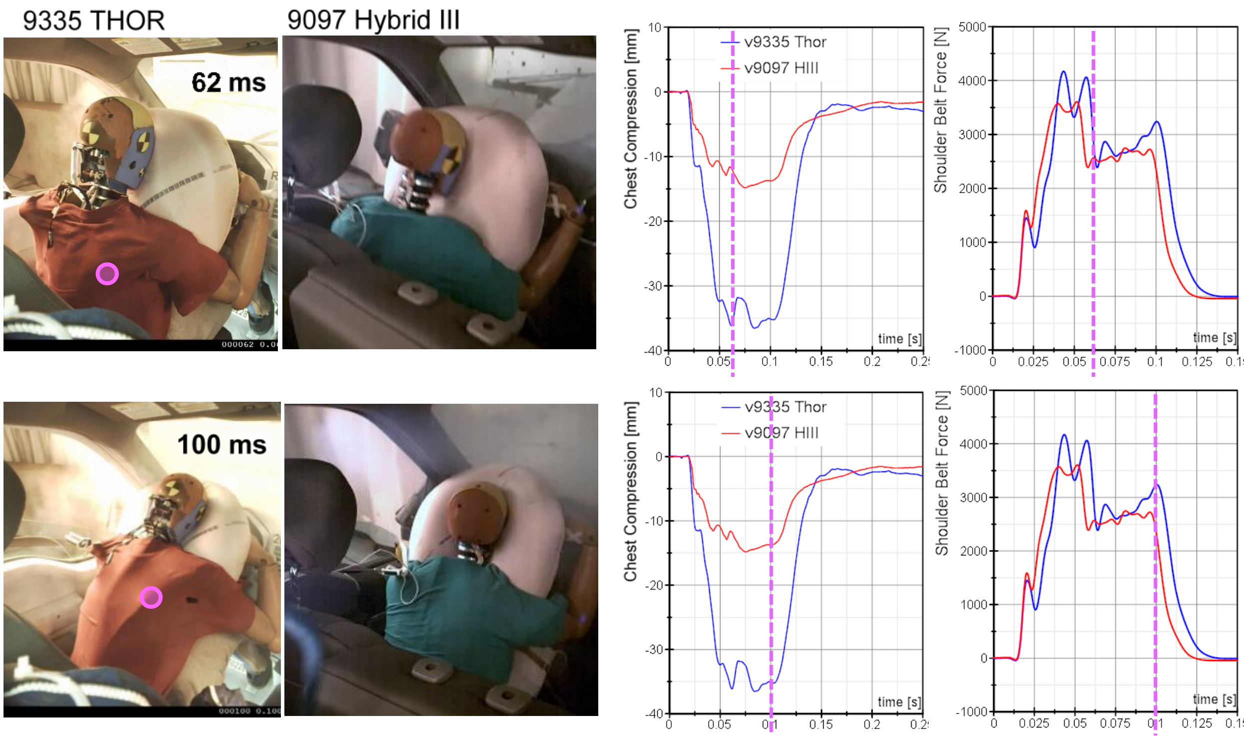


*Figure 4: Chest compression, shoulder belt force, and video stills for the full-sized pickup. 56 km/h frontal rigid barrier. Chest compression is shown at the peak location for THOR (upper right) and the sternum slider for H3. Pink dashed line - time shown in the video captures - showing the time at which the secondary digressive force limits engages, followed by the time of peak forward excursion.*

**DISCUSSION**

These results suggest that in full-vehicle crash tests, the THOR dummy may exhibit sensitivity to combined belt and airbag loading in a manner that is different than the Hybrid III. The differences in sensitivity to airbag loading appear to vary among the fleet, likely dependent on factors such as proximity to the airbag, shape of the airbag, and characteristics of the belt force limiter.

In the case of the subcompact sedan shown here, the chest compression observed in the Hybrid III appears to be almost entirely dependent on the belt force limiter, exhibiting a distinct plateau in chest compression following the yielding of the belt force limiter. In contrast, with the THOR the chest compression continues to increase as the dummy moves into the airbag after the force limiter yields. In the cases of the compact sedan and the mid-sized sedan, the sensitivity appears airbag loading more mixed – the Hybrid III appears to exhibit some increase in chest compression after the force limiter yields, however this is still abbreviated compared to what was observed in the THOR. The THOR and the Hybrid III responses appear to be most similar (in nature) in the case of the full-sized pickup truck with a digressive force limiter. In that case it appears that as the belt force limit drops, engagement with the airbag increases, resulting in a net plateau in chest compression with both dummies.

The differences observed in the contribution of airbag loading to chest compression are not necessarily reflective of differences in sensitivity to airbag loading itself (though that may also be a factor). Instead, this likely represents the combined effects of multiple differences in the construction and response of the dummies that culminates in a difference in how the dummy engages the airbag. With its two flex joints, the spine of the THOR tends to be more flexible than the spine of the Hybrid III [11,13-15]. The chest of the THOR is also more compliant and less structurally-coupled than the Hybrid III [17], and the shoulder allows for degrees-of-freedom not present in the Hybrid III [15]. With these factors combined, the THOR tends to exhibit greater forward excursion compared to the

Hybrid III. In the crash tests examined here, this resulted in the THOR moving forward and riding up on the airbag higher than the Hybrid III, resulting in engagement with the airbag around the region of the upper chest compression measurement locations. Thus, a chain of multiple differences in the design and response of the dummies manifest as context-specific differences in engagement with the restraint system, and differences in sensitivity to loading by the various restraint system components.

The relative sensitivity to belt and airbag loading likely has a direct effect on restraint system optimization. In cases where the Hybrid III response is dominated by sensitivity to the belt force limit, the dummy may suggest that the optimal design would be one where the belt force limit is very low [22]. In contrast, in cases where both the belt and airbag loading contribute comparably to chest compression (such as the THOR in the sub-compact), there likely exists an optimal belt force limit where chest compression is minimized by balancing engagement contributions from the belt and the airbag. Thus, in cases where the sensitivity to loading by the various restraint system components is different between the two dummies, the Hybrid III and the THOR may result in different optimization strategies when designing restraints for that vehicle.

The observation that the relative belt/airbag sensitivity is different across vehicles suggests that it will be difficult to infer if (and how) a transition to THOR would affect systematic trends in restraint optimization and design philosophy. The implications of using one dummy over the other will likely be dependent on the specific characteristics of the vehicle and the restraint systems being studied, with limitations in generalizability.

These results also highlight the importance of evaluating the biofidelity and injury prediction ability of dummies from the context of sensitivity to changes in restraint system design. Dummy biofidelity is most often evaluated by comparing against reference data (e.g., tests with post-mortem human surrogates, PMHS) in a few select testing conditions. The dummy responses in a particular test mode are typically compared to reference results in that test mode, and judged as acceptable or not. This has been codified in recent years by the advent of objective ratings schemes that can aggregate multiple individual test mode comparisons into a single biofidelity score [23-25].

To be useful as a tool to guide restraint design and optimization, however, a dummy must be able to accurately predict how a change in loading condition will affect changes in engagement and injury risk for a human occupant. Existing objective ratings schemes lack a means to incorporate sensitivity to changes in loading condition, and a dummy’s sensitivity to changes in restraint is rarely considered in biofidelity evaluations [3,26]. These results suggest that in some cases the Hybrid III and the THOR exhibit differences in engagement with restraint system components that may result in differences in sensitivity to changes in restraint system design. It is currently unknown which more accurately reflects the sensitivity that would be exhibited by a human occupant. Evaluating dummy biofidelity from the standpoint of sensitivity to changes in loading requires substantially more data than is typically available from PMHS-based experimental datasets. Instead, such an evaluation may require novel means to generate reference targets spanning a wide range of loading conditions using parametric human body modeling, anchored with a select set of physical experiments to spot-check the accuracy of the resulting response surface.

**CONCLUSIONS**

This study sought to compare factors that influence chest compression between the THOR and Hybrid III dummies in matched full vehicle tests publicly available in NHTSA’s Vehicle Crash Test database. Four sets of matched tests were found, and examined for chest compression timing and the relation to engagement with the various components of the restraint system. The observations may be summarized as follows:

- In at least one case, the chest compression in the Hybrid III appeared to be related to predominantly to loading by the shoulder belt, with chest compression plateauing in-phase with yielding of the shoulder belt force limiter. In contrast, the chest compression in the THOR appeared to be affected by a combination of loading by the belt and the airbag, with an increase in chest compression as the dummy moved forward into the airbag. This is likely due to the combined effects of differences in shape and compliance of the shoulder and chest, differences in chest compression measurement location, and differences in the flexibility of the spine (allowing the THOR to move forward, and ride up onto the airbag to a greater degree than the Hybrid III in this case).

- In other cases, the relative sensitivity appeared more mixed, with both dummies exhibiting some chest compression related to both belt and airbag loading. However, in these cases the airbag-related chest compression in the Hybrid III still appeared abbreviated compared to the THOR. The Hybrid III chest compression exhibited a plateauing behavior at some time after belt force limiter yielding, while the THOR chest compression continued to build towards a peak occurring near the time of maximum forward excursion.
- The two dummies exhibited the most similar phasing of chest compression in a case of a vehicle with an apparent digressive belt force limiter. In both dummies the chest compression remained steady as the dummy moved forward into the airbag, after the drop in belt force associated with the digressive limiter.

These results suggest that the mechanisms of chest compression in the two dummies, and the relative sensitivity of the two dummies to differences in restraint design, may be variable dependent on the specific characteristics of the vehicles and restraint systems being evaluated. Thus, in some cases optimized restraint designs may be different for the two dummies, dependent on the specific characteristics of the vehicle and the restraints. These results also highlight the importance of including sensitivity evaluation in biofidelity assessment, evaluating a dummy's (or human body model's) ability to replicate sensitivity to changes in restraint system interaction in a manner reflective of what would occur in a real occupant.

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